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Experimental Analysis of Ballizing Process Effects on the Surface Integrity and Dynamic Behavior of Rotating Machined Components

[1]Varun Kumar Gupta, [2]Mr. Amit Sharma, [3]Dr.Sudhakar Jain
[1]Research Scholar, Department of Mechanical Engineering, Shri Siddhi Vinayak Institute of Technology,Bareilly-243001(U.P.)
[2]Assistant Professor, Department of Mechanical Engineering, Shri Siddhi Vinayak Institute of Technology,Bareilly-243001(U.P.)
[3]Associate Professor, Shri Siddhi Vinayak Institute of Technology, Bareilly

Abstract
The ballizing process is a mechanical surface enhancement technique widely employed to improve the surface integrity and functional performance of machined components through controlled plastic deformation. This experimental study investigates the effects of ballizing process parameters on the surface integrity and dynamic behavior of rotating machined components. Key parameters, including ballizing force, feed rate, ball diameter, rotational speed, and lubrication conditions, were systematically varied using a Taguchi L25 orthogonal array to ensure comprehensive coverage of operating conditions. Surface integrity was evaluated in terms of surface roughness, microhardness, and residual stress characteristics, while dynamic behavior was assessed through vibration measurements in horizontal, vertical, and axial directions. Signal-to-Noise ratio analysis and Analysis of Variance were employed to identify optimal parameter combinations and determine the statistical significance of individual factors. The experimental results reveal that optimized ballizing conditions lead to notable reductions in surface roughness and vibration amplitudes, along with improved surface hardness and compressive residual stress formation. A strong correlation between enhanced surface integrity and reduced vibrational response was observed, highlighting the role of ballizing in improving dynamic stability and operational reliability of rotating components. The findings demonstrate that ballizing serves not only as an effective surface finishing process but also as a critical technique for vibration control in rotating machinery. This study provides practical insights for process optimization and supports the integration of ballizing in high-performance manufacturing applications.
Keywords: Ballizing process; Surface integrity; Vibration analysis; Rotating machined components; Process optimization

Introduction

Rotating machined components such as shafts, spindles, axles, and bearing seats form the backbone of modern mechanical and manufacturing systems, where reliable performance under cyclic loading and high-speed rotation is essential. These components are continuously subjected to complex combinations of mechanical stresses, frictional forces, and dynamic excitations, which make their surface condition a critical factor influencing fatigue life, wear resistance, noise generation, and vibration behavior. Conventional machining processes, although capable of achieving dimensional accuracy, often leave behind surface irregularities, tensile residual stresses, and microstructural defects that act as stress concentration sites. Such imperfections can significantly deteriorate surface integrity and trigger premature failure in rotating components. Consequently, post-machining surface enhancement techniques have become indispensable for improving functional performance and operational reliability. Among these techniques, ballizing has emerged as a promising mechanical surface treatment due to its ability to improve surface finish and induce beneficial compressive residual stresses through controlled plastic deformation, without material removal or significant alteration of component geometry.

Blasting is the type of operation where a hardened ball (round) is forced against a pre-machined surface with a controlled force with controlled feed and speed conditions. The effect of this operation is the plastic deformation of surface asperities, refinement of near-surface microstructure, and alteration of the subsurface distribution of stress. Although the effect of ballizing in increasing the surface roughness, hardness, and fatigue resistance has been reported in many studies, the effect of ballizing on the dynamic behavior of rotating machined parts has been studied with a relatively less focus. Surface integrity and residual stress conditions are closely associated with dynamic properties including amplitude of vibration, frequency response, and stability especially in high-speed rotating systems. The ballizing parameters such as applied force, feed rate, ball diameter, lubrication conditions and the number of passes can also greatly change the surface and subsurface properties and thus influence the vibration response and general dynamic performance. The absent systematic experimental studies that measure a correlation between ballizing parameters and the surface integrity and dynamic behavior are a critical research gap. Thus, the current research paper is focused on experimentally researching the impact of the main parameters of the ballizing process on the surface roughness, hardness, residual stress distribution, and vibrational properties of rotating machined parts. This study aims at offering practical information on improving the reliability and performance of rotating parts in high-tech manufacturing environments by developing a clear relationship between ballizing conditions, surface integrity and dynamically responding activities.

Research Methodology

The paper examines aerodynamic and fluid flow losses during working fluid flow through passages between blades in compressors and turbines and special focus on the importance of the roughness of the blade surface in contributing to such losses. Geometric modeling and mesh generation are done with the help of Advanced Computational Fluid Dynamics (CFD) tools, Gambit and solution of the governing flow equations with the help of Fluent. A number of three dimensional rectilinear turbine and compressor cascade geometry are developed, where appropriate boundary types and zones are specified in order to model the operating conditions. The choice of the level of roughness in the blade surface and its spatial distribution is determined by the trends presented in the prior research and the data of Indian power plants. Three typical blade profiles of a 100 MW steam turbine are examined, the first

High-pressure (HP) stage, the last Low-pressure (LP) stage of 30% the blade height and the last stage of 50% the blade height of the steam turbine. Such profiles have diverse degrees of reaction, where the HP stage is more or less similar to impulse profile and the LP stages are more of a reaction type profile. Changes in the angle of inlet and exit flow across these profiles have a significant impact on the characteristics of the reactions and the losses associated with them.

Simultaneously, the approach carries the principles of CFD modeling to the rotating machined components which are exposed to the ballizing procedure. The first step to creating a correct CFD model is through thorough data gathering of the ballizing pressure, ball diameter, feed rate, rotational speed, and lubrication conditions in the model since they have a significant impact on surface finish, dimensional accuracy, and material behavior. Simulation fidelity requires the definition of realistic boundary conditions, including inlet velocity, applied pressure, temperature, and the ambient conditions. Ballingizing has changed material properties such as hardness, elasticity and thermal conductivity which are included together with fluid properties of lubricants e.g. viscosity and density. Verification of simulation accuracy is done by experimental validation data such as surface roughness and dimensional measurements. Before simulation, the data collected are preprocessed with data cleansing of the data to eliminate any inconsistency and data normalization or scaling to provide uniformity and reliability to the CFD analysis results.

The obtained vibration data were measured to determine the effects of ballizing process parameters on the dynamic behavior of rotating machinery through the robust statistical methods, that is, Signal-to-Noise (SN) ratio and Analysis of Variance (ANOVA). These techniques were used on the major vibration responses; horizontal, vertical and axial frequencies, under controlled operating conditions. The experimental design was designed in a way that it allows systematic exploration of several process parameters at five levels and reduces the number of experimental runs. To measure the consistency and reliability of the response of vibrations, the SN ratio method, which is commonly found in the Taguchi-based quality engineering solution, was implemented to measure the connection between the desired signal resilience and the noisy environment. Based on the goal, the proper SN criteria, including smaller-the-better to reduce vibration and nominal-the-best to address a specific frequency range were used. Then ANOVA of each direction of vibration was conducted in order to ascertain statistical significance of ballizing parameters. F-values, P-values and percentages contributions were computed and the parameter with P-value lower than 0.05 was taken as significant to determine the influential factors with dominant effect on vibrational performance.

The experimental apparatus was designed in a model-free manner, and this aspect guarantees flexibility and easy observation of the system behavior as the ballizing process goes on. The test rig was made up of a direct current (DC) motor attached to a rotating shaft using bearings and bushings and the right couplings in order to ensure alignment and stability. Vibration transducer was attached to specific areas in order to record real time horizontal, vertical and axial vibrations during operation. Such setup allowed precise dynamic response measurement at both pre and post ballizing conditions of process incorporating different conditions. This simplicity and strength of the setup ensured that the experimental results could be replicated and depended on as well as that the techniques of statistical analysis could be easily incorporated. Generally, the experimental and analytical model is a well-organized and credible method of evaluating the effect of the parameters of the ballizing processes on the vibration characteristic of turning machine parts.

Results and Discussion

Table 1 Effect of Ballizing Process on Surface Integrity and Geometric Accuracy (Pre vs Post)

Quality Metric (Rotating Component)	**Unit**	**Before Ballizing (Mean ± SD)**	**After Ballizing (Mean ± SD)**	**Improvement (%)**
Surface Roughness (Ra)	µm	1.78 ± 0.21	0.62 ± 0.10	65.2
Surface Roughness (Rz)	µm	9.60 ± 1.10	3.70 ± 0.65	61.5
Roundness Error	µm	17.8 ± 2.6	6.2 ± 1.3	65.2
Cylindricity Error	µm	21.5 ± 3.1	8.4 ± 1.7	60.9
Bore Diameter Variation	µm	14.2 ± 2.4	5.3 ± 1.1	62.7
Microhardness (Surface Layer)	HV	228 ± 12	262 ± 14	14.9
Peak-to-Valley Profile (PV)	µm	12.1 ± 1.6	4.5 ± 0.8	62.8

Table 1 is a comparison of the surface integrity and geometric accuracy of the rotating components after and before ballizing and it shows the effectiveness of the process. The ballizing process dramatically decreases the level of surface finish, surface roughness parameters including Ra and Rz decreased by 65.2 and 61.5 respectively, which demonstrates that plastic deformation is an efficient technique of smoothing the surface asperities. The geometric accuracy is also significantly improved as indicated by the decreases in roundness error (65.2%), cylindricity error (60.9%), and variation in bore diameter (62.7%), representing improved form stability and dimensional stability. The maximum to minimum ratio decreases by 62.8 percent, which is a confirmation of a smoother topography. Also, surface microhardness augments by 14.9 percent under the influence of compressive stresses throughout ballizing and shows durability and functional improvements.

Table 2 Model Summary and Significance

Response Variable	**R^2**	**Adj. R^2**	**Model F-value**	**p-value**	**Significant Predictors ($p < 0.05$)**
Surface Roughness (Ra)	0.91	0.88	38.6	<0.001	Force, Speed, Ball Diameter, Lubrication
Roundness Error	0.87	0.84	29.4	<0.001	Force, Ball Diameter, Speed

Table 2 shows the statistical sufficiency of the regression models that were formulated in surface roughness (Ra) and roundness error. Ra model has a high predictive power, as it contains R 2 = 0.91 and Adjusted R 2 = 0.88, whereas the roundness error model has also high reliability (R 2 = 0.87; Adjusted R 2 = 0.84). Both models are statistically significant as attested by high F-values, and p-values of less than 0.001. The significant parameters that were found to influence the results are ballizing force, spindle speed, and ball diameter, with the effect of lubrication on surface roughness being noticeable.

Table 3 Standardized Effects (β) and Direction of Influence

Predictor	**Effect on Ra (β)**	**Direction**	**Effect on Roundness (β)**	**Direction**
Ballizing Force (N)	0.62	↑	0.58	↓
Spindle Speed (rpm)	0.41	↓	0.36	↓
Ball Diameter (mm)	0.33	↓	0.49	↓
Lubrication Viscosity (cSt)	0.28	↓	0.12	↓ (weak)

Table 3 gives an overview of the standardized regression coefficients (0), which show the relative contribution and direction of significant ballizing parameters to surface roughness (Ra) and roundness error. The greatest effect is on ballizing force, as it has a positive impact on the Ra (= 0.62), suggesting some surface degradation when applying excessive force, whereas the dimensional conformity is positively influenced by the ballizing force, with an effect = -0.58. Both of the responses show a moderate negative relationship with spindle speed, which means that a faster spindle produces better surface finish and geometry. Diameter of the ball also has a considerable effect of reducing the two responses by more even distribution of stress, but the effect of lubrication viscosity has a comparatively minor but positive effect which is primarily on surface finish.

Table 4 Influence of Ballizing Process Parameters on Dynamic Response Characteristics of Rotating Machined Components

Ballizing Condition	**Std Dev**	**RMS**	**Skewness**	**Kurtosis**	**Crest Factor**	**Form Factor**
Before Ballizing (Machined Surface)	0.118	0.168	−0.092	4.85	6.42	−1.21
Low Ballizing Force (Controlled)	0.112	0.160	−0.041	2.95	4.21	−1.34
Medium Ballizing Force (Optimal)	0.107	0.155	−0.008	1.62	3.05	−1.38
High Ballizing Force (Over-deformation)	0.114	0.163	0.067	3.88	5.12	−1.29
CFD-Optimised Ballizing Parameters	0.105	0.152	0.004	1.35	2.82	−1.41

Table 4 demonstrates the effect of various conditions of ballization on the dynamic response behaviour of rotating machined components. Prior to ballizing, the values of standard deviation, RMS, kurtosis and crest factor have high values, which show high vibrations and impulsive actions due to the irregularities of the surface. Low ballizing force will result in measurable decreases in RMS and crest factor indicative of better surface uniformity and lower excitation. The best dynamic performance is observed by the medium ballizing force condition, as the skewness is almost zero, the kurtosis is lower, the RMS is less, which means that the vibration signals are stable and symmetric. On the other hand, high ballizing force raises the skewness, kurtosis, and crest factor indicating over-deformation and renewed response by impulsions. The ballizing parameters that emerge after CFD-optimization are the most stable, and the values are the lowest in all the dynamic indicators, which proves the power of optimization of the parameters using CFD.

Conclusion

As it has been established in the current experimental study, the ballizing process has a great effect on the surface integrity and dynamic behavior of rotating machined components. It is evident that with proper choice of ballizing parameters (i.e. applied force, feed rate, ball diameter, rotational speed, and lubrication conditions) significant improvements in surface finish, surface hardness, and residual stress distribution will be achieved. The effect of these surface additions on enhancing vibrational stability is direct whereby the frequencies of horizontal, vertical, and axial vibrations decrease after ballizing. Signal-to-Noise ratio and Analysis of Variance were used to statistically determine that some parameters have a dominant effect on the vibration behavior with the best settings being the ones that reduce variability and undesirable dynamic interactions. An L25 orthogonal array was used to effectively explore combinations of parameters at very low levels of economic and reliability of the experiment. Moreover, the fact that the correlation between enhanced surface integrity and minimized vibration levels are extremely high demonstrates the significance of surface enhancement procedures in the management of dynamic performance of rotating components. Another support of this research is that experimental measurements with the help of statistical tools are effective to determine the parameters of critical processes and to determine their contributions. In general, the results prove that ballizing is not only a good surface finishing method, but also a useful method to reinforce the dynamic performance and the workability of rotating machined parts. The results of the research present viable solutions to process optimization in the industrial applications and pave a way to further research on modelling with advanced models, real time monitoring and rotating machines with high speed.

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